공학석사학위논문

A Multi-period Stackelberg Game for Renewable Power Capacity Expansion in Renewable Portfolio Standard

재생에너지 공급의무화제도하에서 재생에너지 발전용량 확장을 위한 다기간 슈타켈버그 게임

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Abstract

A Multi-period Stackelberg Game for Renewable Power Capacity Expansion in Renewable Portfolio Standard

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Under renewable portfolio standard (RPS), the government provides a long-term plan of quota obligation of renewable energy generation imposed on conventional large-scale power generation firms to the market. In this thesis, we propose a multi-period Stackelberg game to model the competition between the conventional generation firm and renewable energy generation firm, and analyze the effect of the quota obligation and other key variables on the proliferation of renewable energy. We proved that the proposed model has a unique Nash equilibrium, and based on this, numerical experiments were conducted to analyze RPS system. We found that the optimal solutions of multi-period model and single-period model are different, and the reason is that determining the optimal renewable energy capacity expansion at each period is inefficient rather than establishing a multi-period optimal strategy at once. We also found that there is an optimal REC weight that maximizes the proliferation of renewable energy. Finally, we found that the rate of increase in demand in the power market and the rate of increase in quota obligation are synergistic with each other from the perspective of renewable energy diffusion.

Keywords: Renewable energy, Renewable portfolio standard, Multi-period Stackelberg game, Renewable support scheme, Electricity market
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Chapter 1

Introduction

1.1 Motivation

To cope with climate change, countries around the world apply various eco-friendly policies to industries, public, private and commercial sectors. In the field of industries with large greenhouse gas emissions, there are emission trading scheme (ETS) that typically limit carbon emissions. Especially in the energy industry, there are renewable portfolio standard (RPS) and feed-in tariff (FiT) for the development of renewable energy. FiT is a price-based policy that obligates electric utilities to purchase electricity produced by renewable energy at government-set tariffs and guarantees it for a certain period of time. RPS is a system that mandates fossil fuel power generation companies to produce a specific ratio of total power generation as renewable energy, and is currently adopted and utilized in many countries, such as Korea, the United States, and China. In the early stages of the introduction of RPS, the government proposes a long-term plan for imposing new and renewable energy in the electricity market, and power generation companies directly produce new and renewable energy or purchase renewable energy certificate (REC) from other power generation companies in order to meet the annual requirements.

Under RPS, existing fossil fuel power generation companies and renewable energy power generation companies, which are new participants in the power generation market, are in a competitive relationship in that they produce electricity. In particular, REC, which is given in proportion to the amount of renewable energy generation, acts as an additional source of revenue other than electricity sales for new and renewable energy generation companies, but it also acts as a cause of lowering profitability when purchasing to fill the obligation for fossil fuel generation companies. Therefore, if it is possible to predict how the long-term plan to impose mandatory obligations on renewable energy generation under RPS will affect the proliferation of new and renewable energy and the profitability of each power generation company, it will contribute to the government's effective renewable energy policy setting.

1.2 Problem Description

This study assumes that the power market is a duopoly market structure in which one large-scale fossil fuel power generation company and one renewable energy power generation company participate. Figure 1.1 represents the competition between the two companies under renewable portfolio standard. In RPS system, government impose a long-term renewable energy supply obligation on the large-scale power generation companies at the beginning of RPS introduction. The large-scale power generation company and the renewable energy generation company basically compete in electricity production in the power market, and the price of electricity is determined by consumer demand and supply of the producers. The two companies participate not only in the power market but also in the green certificate market, where the renewable energy generator is REC supplier and the large-scale power generation company is REC consumer. Therefore, the large-scale power generation company decide whether to purchase REC in the GC market or to produce REC through renewable energy generation itself. Then, the large-scale power generation company meet its obligation by submitting secured RECs to the government. The large-scale power generation operator is the leader of competition in that its influence in the power market is greater than that of renewable energy generation operator and that decides the amount of REC purchases that determine the profitability of renewable energy operator. On the other hand, the renewable energy power generation company is the follower in that it newly participate in the electric power market and its profit is determined dependent on the decision of the large-scale power generation company. Thus, the leader and the follower determine the electricity output that maximizes their respective profits. In this situation, we propose a two stage multi-period Stackelberg game to model the competition of electric power production between existing fossil fuel power generation company and renewable power generation company, which is new market participant.

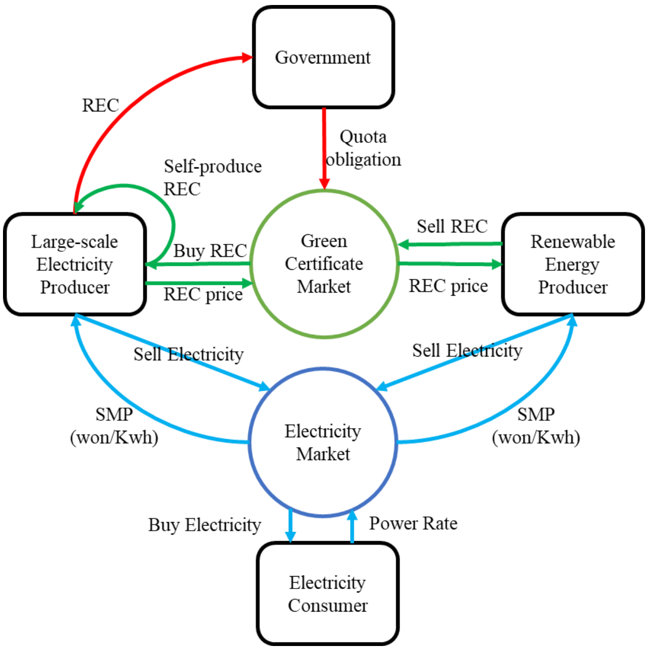

Figure 1.1: Market structure under renewable portfolio standard

1.3 Organization of the Thesis

The thesis is composed of 5 chapters. In Chapter 2, we review literatures related to the problem. In Chapter 3, we propose Stackelberg game for renewable power capacity expansion. In Chapter 4, numerical examples and results of analysis are presented. Finally, in Chapter 5, we give concluding remarks.

Chapter 2

Literature Review

Research related to renewable energy policy has been continuously conducted, and research on the RPS system, which has begun to be used relatively recently, is actively being conducted.[1, 2, 3, 4, 5, 6] Careri. F., et al[7] modeled the optimal power generation capacity expansion plan for eco-friendly development considering FiT, RPS, carbon emission, carbon tax, etc. and applied to Italian power market to maximize the suspension of net profit and propose a power expansion plan for each power generation source satisfying environmental characteristics.

Hustveit, M., et al.[8] developed a estimation model based on dynamic planning method to evaluate the performance of the RPS system, analyzed the REC trading market in Sweden-Norway, and argued that the price of REC would start at the current price range and reach 0 won when the government's renewable energy policy ends. Xin-gang, Z., et al.[9] developed a model for finding REC prices that maximize social wellbeing by utilizing system dynamics and analyzed China's REC trading market, resulting in a rise in total power output and a fall in electricity prices as REC prices increased, and presented REC prices that maximized both producers, consumers and social wellbeing.

Studies on the competition among power generation companies in the electric power market have been actively conducted.[10, 11, 12, 13, 14, 15] Tamás, M., et al.[16] compared and analyzed the performance of FiT and RPS in the fully competitive and incomplete markets when eco-friendly power generators and fossil fuel power generators compete for power production, and argued that in the fully competitive market, the price of FiT subsidies and RECs are completely the same, and when applied to the UK power market, RPS increases social welfare than FiT.

Ghaffari, M., et al. [17] modeled the competition of the power generation market under RPS into three types: Courtnot, Stackelberg, and cooperative games for a single-period of time, and presented a Nash equilibrium. The price of electricity, renewable energy production, and the profits of each power generation company were analyzed by applying various scenarios. Pineda, S., & Bock, A.[18] have modeled the competition in the power generation market and the expansion of renewable energy capacity as a multi-period Cournot competition, presenting renewable energy production and social welfare by various scenarios in the Danish power market and deriving the mandate to supply renewable energy to maximize renewable energy capacity.

Fang, D., et al.[19] modeled the relationship between the government and power generation companies and the competition between existing fossil fuel power generation companies and renewable energy power generation companies through evolutionary games, and concluded that the government's dynamic subsidies and fines policies would help to increase policy effects and reach a long-term balance. Zhao, X. G., et al.[20] analyzed the competition of the power generation market by applying it to the power market of China through the evolution game and found that REC's transaction cost and marginal cost were reduced when the optimum capacity of renewable energy generation was given to the market, thereby increasing the effectiveness of RPS.

In the previous studies, RPS performance evaluation, power capacity expansion plans, and analysis of the electricity market and REC transaction market considering competition were conducted. However, there is a limitation that most researchers use only the final goal of the long-term renewable energy supply plan proposed by the government at the beginning of the introduction under the RPS. In addition, the long-term power generation competition between electricity generation companies was not considered. Moreover, the situation in which the existing fossil fuel generators produce renewable energy by themselves and meet the supply obligation is not considered, and the REC weight of each renewable energy source is not considered.

Chapter 3

Stackelberg Game for Renewable Power Capacity Expansion

3.1 Basic Assumptions and Model Settings

In this study, we assume the electricity market as a duopoly which consists of the leader and the follower that produce homogeneous product. The government presents a long-term quota obligation plan to the market at the beginning of RPS introduction. Here, the leader is a large-scale power generation company that was a monopolist of the power market with fossil fuels, and the follower is a renewable energy power generation company that participates in the market with the introduction of RPS. It is assumed that the follower participates in the electricity generation market by utilizing single renewable energy technology. The leader already has a large-scale fossil fuel power generation facility, and in order to meet quota obligations, it generates renewable energy itself to acquire RECs or purchases RECs from the follower. We assume that the leader also utilizes only one renewable energy technology, and both companies may choose different technologies. In this study, the investment and operation cost per unit power output of renewable energy power generation facilities was set at an annual equivalent cost, and it is assumed that it does not change over time. It is also assumed that the salvage value of a renewable energy facility is equal to the sum of annual equivalent costs over the remaining useful life. The annual equivalent cost of the technology adopted by the leader was set as c_F, and the annual equivalent cost of the follower's technology was set as c_S. Furthermore, it is assumed that the renewable energy generation facilities are always fully utilized to ensure economic feasibility. Therefore, companies cannot freely control the electricity to be produced by the installed renewable energy generation facilities, and the capacity of the renewable energy should be increased in order to produce additional electricity. Moreover, expanding the capacity of renewable energy facilities to produce 1MWh of electricity does not mean a one-time purchase decision of the facility, but rather maintains the ability to produce the same amount continuously. At each time t, the amount of electricity produced by the leader with fossil fuel was set to $x_{1,t}$, and the amount of electricity that can be newly produced by expanding the renewable energy facility capacity was set to $x_{2,t}$. Similarly, the amount of power that the follower can produce by increasing the capacity of the renewable energy facility at each time t was set to y_t. The cost of fossil fuel generation per unit power production is assumed to follow quadratic form, and the production cost is $ax_{1,t}^2 + bx_{1,t} + d$.

In this study, it is assumed that the electricity price in the power market is determined by the inverse demand function, and the electricity price at time t is $P_t(Q_t) = \alpha - \beta Q_t + \gamma t$ when the total power amount produced by the two companies is Q_t. According to the inverse demand function, the demand for the power market increases in proportion to the time t. Each power generation company acquires REC in proportion to the unit renewable energy power production, and different REC weights are multiplied according to the type of technology used. In general, governments place higher weights on renewables with higher unit production costs to ensure economic feasibility. The weight of the renewable energy generation technology utilized by the leader is set to δ_X , the weight of the power technology is set to δ_Y . In this study, REC price e_t is assumed to be a constant that varies over time. The government imposes a long-term quota obligation on the market at the beginning of its introduction, and it is assumed that the follower always meets the obligation K_t . Furthermore, we assume that the certificate, which the follower failed to sell to the leader, would expire at the next time period. Finally, this study assumes that the leader does not produce renewable energy beyond quota obligation as a reason for reducing total production costs.

3.2 Existence and Uniqueness of optimal solution

In Stackelberg games, each competitor finds the optimal solution of the decision variables that maximize their revenue. If all companies are rational and have a unique optimal solution, then the solution set is the unique Nash equilibrium of the problem. Therefore, to predict the optimal strategy of each company in a given situation, we first need to prove all competitor's optimization problem has a unique optimal solution. The conditions for the existence and uniqueness of an optimal solution in the optimization problem are as follows.

Definition 3.1. *Let* $\overline{f}(x)$ *an extended-valued function.* $\overline{f}:\mathbb{R}^2 \to [-\infty,+\infty]$ *which is equal to* f *for* $x \in \chi$ *and equal to* $+\infty$ *otherwise.* $f(x)$ *is a proper function if* $\overline{f} < +\infty$ *for at least one* $x \in \mathbb{R}^n$ *and* $\overline{f}(x) > -\infty$.

Definition 3.2. *A proper function* $f:\mathbb{R}^n \to (-\infty,+\infty]$ *is called coercive if* $\lim_{\|X\|\to\infty} f(x)=\infty$.

Lemma 3.1. *If* $\chi \subseteq dom\, f$ *is nonempty and closed, and* f *is continuous on* χ *and coercive, then problem attains an optimal solution* x^*.

Lemma 3.2. *Intersection of closed sets is closed.*

Lemma 3.3. $\nabla^2 f > 0$ *for all* $x \in dom\, f$ *implies that* f *is strictly convex.*

Lemma 3.4. *Asymmetric matrix* $F(x)$ *is positive definite if and only if all of the leading principal minors are positive.*

Definition 3.3. *A constraint of the form* $AX - B \sim 0$ *where* A *is a coefficient vector,* B *is a real scalar,* X *is a vector of variables and* $\sim$ *is one of* $\leq, \geq$ or $=$ *is and affine constraint.*

Lemma 3.5. *Affine set is a convex set.*

Lemma 3.6. *If* f *is a strictly convex function,* χ *is a convex set, and* x^* *is an optimal solution to the problem, then* x^* *is the unique optimal solution.*

Lemma 3.7. *Let* $A \in \mathbb{S}^n$, $B \in \mathbb{S}^m$, $X \in \mathbb{R}^{n+m}$ *with* $B \succ 0$. *Consider the symmetric block matrix* $M = \begin{bmatrix} A & X \\ X^T & B \end{bmatrix}$ *and define the so-called Schur complement matrix of* A *in* M. *If* $S = A - XB^{-1}X^T$ *then,* $M \succ 0 \Leftrightarrow S \succ 0$.

3.3 Single-period Stackelberg game

A single-period Stackelberg game assumes that the final goal of quota obligation is presented in the market and analyzes the optimal decision making of the leader and the follower. Although this model is simple and easy to solve, it has the disadvantage that it does not reflect the annually increasing quota obligation, the increase in electricity market demand, and changes in various variables.

The follower's total profit Π_y is as follows.

$$\Pi_y = (\alpha - \beta(x_1 + x_2 + y)) \cdot y - c_s \cdot y + e_0 \cdot ((x_1 + x_2) \cdot k_0 - \delta_x \cdot x_2) \tag{3.1}$$

(3.1) is the sum of electricity sales and REC sales subtracting renewable energy facility expansion costs. Now we can formulate the follower's problem as follows.

$$\max_y \quad \Pi_y \tag{3.2}$$

$$\text{subject to} \quad y \geq 0 \tag{3.3}$$

(3.2) is an objective function of the follower's problem and (3.3) imposes a positive installed capacity.

Similarly, the leader's profit is as follows.

$$\begin{aligned}\Pi_x &= (\alpha-\beta(x_1+x_2+y))\cdot(x_1+x_2)-(ax_1^2+bx_1+d)-c_F\cdot x_2\\ &\quad -e_0\cdot((x_1+x_2)\cdot k_0-\delta_x\cdot x_2)\end{aligned} \tag{3.4}$$

Now we can formulate the leader's problem as follows.

$$\max_{x_1,x_2} \quad \Pi_x \tag{3.5}$$

$$\text{subject to} \quad (x_1+x_2)\cdot k_0-\delta_X\cdot x_2\geq 0 \tag{3.6}$$

$$(x_1+x_2)\cdot k_0-\delta_X\cdot x_2\leq \delta_Y\cdot y \tag{3.7}$$

$$\alpha-\beta(x_1+x_2+y)\geq c_s \tag{3.8}$$

$$x_1,x_2\geq 0 \tag{3.9}$$

(3.5) is an objective function of the leader's problem. The constraints (3.6) and (3.7) are that the amount of REC the leader must purchase is greater than or equal to 0 and smaller or equal to the amount produced by the follower. Constraint (3.8) ensures the minimum profitability of the renewable energy generation company, as the leader is conditioned by the government that the electricity price must be at least greater than or equal to the investment cost of renewable energy. (3.9) imposes positive generation of electricity for both fossil fuel and renewable energy.

In order to show that there is a unique Nash equilibrium in this problem, we first show that the problem of the follower has a unique optimal solution assuming that the decision variables of the leader are given. The first order condition of the follower's objective function is as follows.

$$\frac{d\Pi_y}{dy} = \alpha - \beta(x_1 + x_2) - 2\beta y - c_S = 0 \tag{3.10}$$

Then, we can obtain

$$y^* = \frac{\alpha - c_S}{2\beta} - \frac{1}{2}(x_1 + x_2) \tag{3.11}$$

By constraint (3.8), $y^* \geq 0$. Therefore, (3.11) is a unique optimal solution of the follower's problem at the second stage. At the first stage, the leader optimizes his own goal by taking into account the rational reaction of the follower. Substituting for y from the follower's problem, the leader gets updated problem as follows.

$$\begin{aligned} \max_{x_1, x_2} \quad & \frac{1}{2}(\alpha + c_S - \beta(x_1 + x_2)) \cdot (x_1 + x_2) - (ax_1^2 + bx_1 + d) \\ & \qquad -c_F \cdot x_2 - e_0 \cdot ((x_1 + x_2) \cdot k_0 - \delta_x \cdot x_2) = \Pi'_x \end{aligned} \tag{3.12}$$

$$\text{subject to} \quad (x_1 + x_2) \cdot k_0 - \delta_X \cdot x_2 \geq 0 \tag{3.13}$$

$$(k_0 + \frac{\delta_Y}{2}) \cdot x_1 + (k_0 + \frac{\delta_Y}{2} - \delta_Y) \cdot x_2 \leq \frac{\alpha - c_S}{2\beta} \cdot \delta_Y \tag{3.14}$$

$$\alpha - c_S - \beta(x_1 + x_2) \geq 0 \tag{3.15}$$

$$x_1, x_2 \geq 0 \tag{3.16}$$

Now let's show that the modified problem of the leader has a unique optimal solution. As each constraint (3.13)-(3.16) is closed set, by 3.2, the feasible set which is the intersection of the constraints is nonempty closed set. In addition, Π'_x is continuous on the feasible set, and $-\Pi'_x$ is coercive as $\lim_{\|X\|\to\infty} -\Pi'_x = \infty$. By Lemma 3.1, the modified problem of the leader has an optimal solution.

The constraints are affine set, and the feasible set is convex by Lemma 3.5. As we already have shown that the leader's problem has an optimal solution, showing concavity of the objective function is sufficient condition to prove the uniqueness of the solution by Lemma 3.6. The process of showing that $-\Pi'_x$ is strictly convex is as follows.

$$\frac{\partial \Pi'_x}{\partial x_1} = -\beta(x_1 + x_2) - (2ax_1 + b) + \frac{1}{2}(\alpha + c_S) - e_0 k_0 \tag{3.17}$$

$$\frac{\partial \Pi'_x}{\partial x_2} = -\beta(x_1 + x_2) + \frac{1}{2}(\alpha + c_S) - c_F - e_0(k_0 - \delta_x) \tag{3.18}$$

Differentiating (3.17), (3.18), we can obtain

$$\frac{\partial^2 \Pi'_x}{\partial x_1 \partial x_2} = \frac{\partial^2 \Pi'_x}{\partial x_2 \partial x_1} - \beta \tag{3.19}$$

$$\frac{\partial^2 \Pi'_x}{\partial x_1^2} = -\beta - 2a \tag{3.20}$$

$$\frac{\partial^2 \Pi'_x}{\partial x_2^2} = -\beta \tag{3.21}$$

Then, $-\nabla^2\Pi' = \begin{pmatrix} \beta+2a & \beta \\ \beta & \beta \end{pmatrix} \succ 0$ where $\beta > 0, a > 0$. By Lemma 3.6, we finally proved that the single-period Stackelberg game has a unique Nash equilibrium.

3.4 Multi-period Stackelberg game

In the real world, the government plans to gradually spread renewable energy, and the price of electricity and REC change over time. Moreover, as market demand for electricity increases gradually every year, analysis using the single-period Stackelberg game is relatively less realistic. The multi-period Stackelberg game model, on the other hand, can derive the optimal strategy for each company at every point in time, enabling more effective and realistic analysis of the RPS system. Figure 3.1 depicts the multi-period Stackelberg game of the duopolists in RPS system. When the government presents the quota obligation plan from time 0 to T to the electric power market, based on this information, the conventional electricity producer determines fossil fuel production $x_{1,t}$ and renewable energy facility capacity expansion $x_{2,t}$ for all time period at the first stage. In the second phase, the renewable energy producer then determines the amount of facility capacity expansion at each point in time y_t that maximizes its revenue. Since $x_{2,t}$ and y_t are the amount of power newly generated by the leader and the follower at time t, respectively, the actual amount of electricity produced by renewable energy at time t is $\sum_{i=0}^{t} x_{2,i}$ and $\sum_{i=0}^{t} y_i$, respectively.

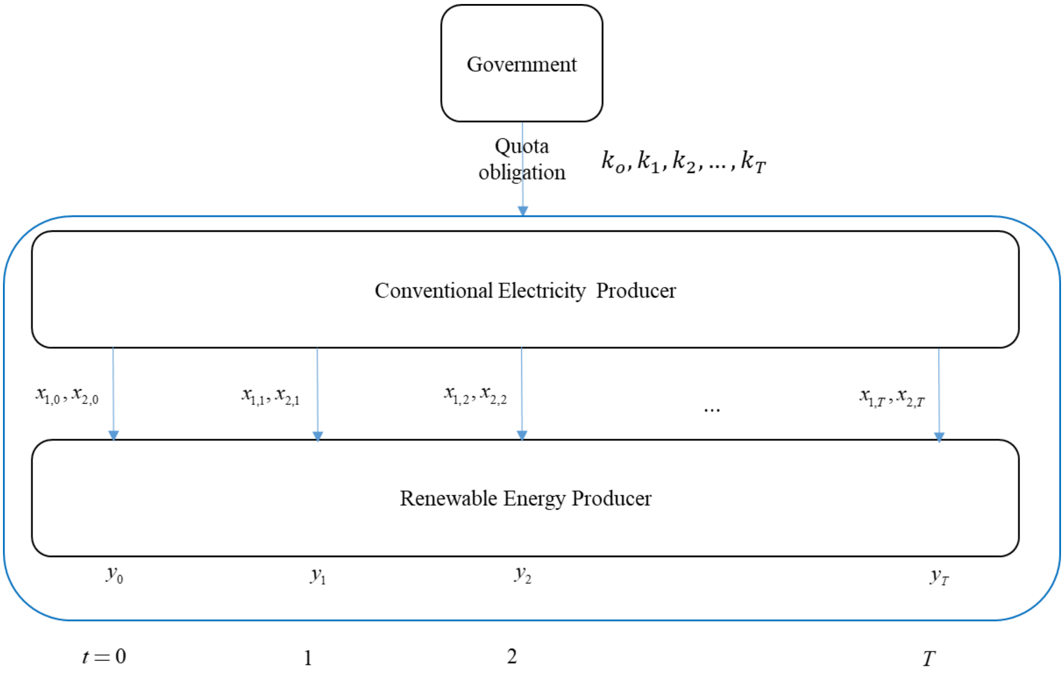

Figure 3.1: A multi-period Stackelberg game in renewable portfolio standard

Let $R = 1/(1+r)$ where $0 \le r \le 1$ is interest rate. Then, the follower's discounted total profit Π_Y is as follows.

$$\begin{aligned}\Pi_Y = \sum_{t=0}^{T} R^t \cdot [((\alpha+\gamma\cdot t) - \beta(x_{1,t} + \sum_{i=0}^{t} x_{2,i} + \sum_{i=0}^{t} y_i)) \cdot \sum_{i=0}^{t} y_i \\ - c_s \cdot \sum_{i=0}^{t} y_i + e_t \cdot ((x_{1,t} + \sum_{i=0}^{t} x_{2,i}) \cdot k_t - \delta_X \cdot \sum_{i=0}^{t} x_{2,i})]\end{aligned} \tag{3.22}$$

(3.22) is the follower's discounted profit determined as the revenue obtained in the electricity market and REC market minus capacity expansion cost. Then, the follower's optimization problem is as follows.

$$\max_{y_t} \quad \Pi_Y \tag{3.23}$$

$$\text{subject to} \quad \sum_{i=0}^{t} y_i \geq 0 \qquad \forall t = 0,1,\cdots,T \tag{3.24}$$

(3.23) is the objective function of the follower which maximizes the discounted total profit. (3.24) imposes a positive cumulative installed capacity for all time period. It means that y_t can be both positive and negative value, so that the firm not only can expand the capacity but also be able to decrease the capacity while satisfying the nonnegativity of total installed capacity. Therefore, the follower does not need to always increase or maintain the capacity of renewable energy generation facilities, and there is an option to reduce the capacity at any time to maximize its profit. Similarly, the leader's discounted profit Π_X is as follows.

$$\begin{aligned}\Pi_X = \sum_{t=0}^{T} R^t \cdot [((\alpha + \gamma \cdot t) - \beta(x_{1,t} + \sum_{i=0}^{t} x_{2,i} + \sum_{i=0}^{t} y_i)) \cdot (x_{1,t} + \sum_{i=0}^{t} x_{2,i}) \\ -(ax_{1,t}^2 + bx_{1,t} + d) - c_F \cdot \sum_{i=0}^{t} x_{2,i} - e_t \cdot ((x_{1,t} + \sum_{i=0}^{t} x_{2,i}) \cdot k_t - \delta_X \cdot \sum_{i=0}^{t} x_{2,i})]\end{aligned} \tag{3.25}$$

(3.22) is the leader's discounted profit determined as the revenue obtained in the electricity market minus capacity expansion cost minus fossil fuel generation cost minus REC purchasing cost. Now we can formulate the leader's optimization problem as follows.

$$\max_{x_{1,t},x_{2,t}} \quad \Pi_X \tag{3.26}$$

$$\text{s.t.}\quad (x_{1,t}+\sum_{i=0}^{t}x_{2,i})\cdot k_t-\delta_X\cdot\sum_{i=0}^{t}x_{2,i}\geq 0 \qquad \forall t=0,1,\ldots,T \tag{3.27}$$

$$(x_{1,t}+\sum_{i=0}^{t}x_{2,i})\cdot k_t-\delta_X\cdot\sum_{i=0}^{t}x_{2,i}\leq \delta_Y\cdot\sum_{i=0}^{t}y_i \qquad \forall t=0,1,\ldots,T \tag{3.28}$$

$$(\alpha+\gamma\cdot t)-\beta(x_{1,T}+\sum_{i=0}^{T}x_{2,i}+\sum_{i=0}^{T}y_i)\geq c_S \qquad \forall t=0,1,\ldots,T \tag{3.29}$$

$$\sum_{i=0}^{t}x_{2,i}\geq 0 \qquad \forall t=0,1,\cdots,T \tag{3.30}$$

$$x_{1,t}\geq 0 \qquad \forall t=0,1,\ldots,T \tag{3.31}$$

(3.26) is an objective function of the leader's problem. The constraints (3.27) and (3.28) are that the amount of REC the leader must purchase is greater than or equal to 0 and smaller or equal to the amount produced by the follower. Constraint (3.29) ensures the minimum profitability of the renewable energy generation company, as the leader is conditioned by the government that the electricity price must be at least greater than or equal to the investment cost of renewable energy. (3.30) imposes a positive cumulative installed renewable energy capacity for all time period. (3.31) constrains generation of electricity by fossil fuel to be nonnegative.

Theorem 3.1. The follower's optimization problem (3.23)-(3.24) in multi-period Stackelberg game has a unique optimal solution.

Proof.

Step1. Existence of optimal solution.

i. Each constraint (3.24) is closed set. Intersection of these constraints ψ (feasible set) is nonempty closed set.

ii. Π_Y is continuous on ψ.

iii. $\lim_{\|Y\|\to\infty} -\Pi_Y = \infty$ and $-\Pi_Y$ is a proper function.

$\therefore$ This problem attains an optimal solution Y^* by Lemma 3.1.

Step2. Uniqueness of optimal solution.

i. ψ is convex because constraints are affine set.

ii. We already showed that this problem has an optimal solution.

iii. Let's show that $-\Pi_Y$ is strictly convex.

Let Π_Y^l as follows.

$$\Pi_Y^l = R^l \cdot ((\alpha + \gamma \cdot l) - \beta(x_{1,l} + \sum_{i=0}^{l} x_{2,i} + \sum_{i=0}^{l} y_i)) \cdot \sum_{i=0}^{l} y_i - c_s \cdot \sum_{i=0}^{l} y_i$$
$$+ e_l \cdot ((x_{1,l} + \sum_{i=0}^{l} x_{2,i}) \cdot k_l - \delta_X \cdot \sum_{i=0}^{l} x_{2,i})]$$

if $l < t$,

$$\frac{\partial \Pi_Y^l}{\partial y_t} = 0 \qquad (\because y_t \text{ does not exist on } \Pi_Y^l)$$

if $l = t$,

$$\frac{\partial \Pi_Y^t}{\partial y_t} = R^t \cdot [-\beta \sum_{i=0}^{t} y_i + (\alpha + \gamma \cdot t - \beta(x_{1,t} + \sum_{i=0}^{t} x_{2,t} + \sum_{i=0}^{t} y_i)) - c_S]$$

if $l > t$,

$$\frac{\partial \Pi_Y^l}{\partial y_t} = R^l \cdot [-\beta \sum_{i=0}^{l} y_i + (\alpha + \gamma \cdot l - \beta(x_{1,l} + \sum_{i=0}^{l} x_{2,t} + \sum_{i=0}^{l} y_i)) - c_s]$$

$$\frac{\partial \Pi_Y}{\partial y_t} = \sum_{l=0}^{T} \frac{\partial \Pi_Y^l}{\partial y_t} = \sum_{l=t}^{T} R^l \cdot (-\beta \sum_{i=0}^{l} y_i + (\alpha + \gamma \cdot l - c_s - \beta(x_{1,l} + \sum_{i=0}^{l} x_{2,t} + \sum_{i=0}^{l} y_i)))$$

$Let\ t_2 > t_1$,

$$\frac{\partial^2 \Pi_Y}{\partial y_{t_1}^2} = -2\beta(R^{t_1} + R^{t_1+1} + \cdots R^T)$$

$$\frac{\partial^2 \Pi_Y}{\partial y_{t_1} \partial y_{t_2}} = \frac{\partial^2 \Pi_Y}{\partial y_{t_2} \partial y_{t_1}} = -2\beta(R^{t_2} + R^{t_2+1} + \cdots + R^T)$$

So, we can obtain

$$\nabla^2 \Pi_Y = -2\beta \cdot \begin{pmatrix} R^T+R^{T-1}+\cdots+R^0 & R^T+R^{T-1}+\cdots+R^1 & R^T+R^{T-1}+\cdots+R^2 & & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1} & R^T \\ R^T+R^{T-1}+\cdots+R^1 & R^T+R^{T-1}+\cdots+R^1 & R^T+R^{T-1}+\cdots+R^2 & \dots & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1} & R^T \\ R^T+R^{T-1}+\cdots+R^2 & R^T+R^{T-1}+\cdots+R^2 & R^T+R^{T-1}+\cdots+R^2 & & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1} & R^T \\ & \vdots & & \ddots & & \vdots & \\ R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1}+R^{T-2} & & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1} & R^T \\ R^T+R^{T-1} & R^T+R^{T-1} & R^T+R^{T-1} & \cdots & R^T+R^{T-1} & R^T+R^{T-1} & R^T \\ R^T & R^T & R^T & & R^T & R^T & R^T \end{pmatrix}$$

$$Let\ \mathbb{T} = \begin{pmatrix} R^T+R^{T-1}+\cdots+R^0 & R^T+R^{T-1}+\cdots+R^1 & R^T+R^{T-1}+\cdots+R^2 & & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1} & R^T \\ R^T+R^{T-1}+\cdots+R^1 & R^T+R^{T-1}+\cdots+R^1 & R^T+R^{T-1}+\cdots+R^2 & \dots & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1} & R^T \\ R^T+R^{T-1}+\cdots+R^2 & R^T+R^{T-1}+\cdots+R^2 & R^T+R^{T-1}+\cdots+R^2 & & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1} & R^T \\ & \vdots & & \ddots & & \vdots & \\ R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1}+R^{T-2} & & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1} & R^T \\ R^T+R^{T-1} & R^T+R^{T-1} & R^T+R^{T-1} & \cdots & R^T+R^{T-1} & R^T+R^{T-1} & R^T \\ R^T & R^T & R^T & & R^T & R^T & R^T \end{pmatrix}$$

Then the principal minors of $\mathbb{T}$ is as follows.

$$\begin{vmatrix} R^T+R^{T-1}+\cdots+R^0 & R^T+R^{T-1}+\cdots+R^1 \\ R^T+R^{T-1}+\cdots+R^1 & R^T+R^{T-1}+\cdots+R^1 \end{vmatrix} = \begin{vmatrix} R^0 & 0 \\ R^T+R^{T-1}+\cdots+R^1 & R^T+R^{T-1}+\cdots+R^1 \end{vmatrix} = R^0 \cdot (R^T+R^{T-1}+\cdots+R^1) > 0$$

$$\begin{vmatrix} R^T+R^{T-1}+\cdots+R^0 & R^T+R^{T-1}+\cdots+R^1 & R^T+R^{T-1}+\cdots+R^2 \\ R^T+R^{T-1}+\cdots+R^1 & R^T+R^{T-1}+\cdots+R^1 & R^T+R^{T-1}+\cdots+R^2 \\ R^T+R^{T-1}+\cdots+R^2 & R^T+R^{T-1}+\cdots+R^2 & R^T+R^{T-1}+\cdots+R^2 \end{vmatrix} = \begin{vmatrix} R^0 & 0 & 0 \\ R^1 & R^1 & 0 \\ R^T+R^{T-1}+\cdots+R^2 & R^T+R^{T-1}+\cdots+R^2 & R^T+R^{T-1}+\cdots+R^2 \end{vmatrix}$$

$$= R^0 \cdot R^1 \cdot (R^T+R^{T-1}+\cdots+R^2) > 0$$

$\vdots$

$$\begin{vmatrix} R^T+R^{T-1}+\cdots+R^0 & R^T+R^{T-1}+\cdots+R^1 & R^T+R^{T-1}+\cdots+R^2 & & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1} & R^T \\ R^T+R^{T-1}+\cdots+R^1 & R^T+R^{T-1}+\cdots+R^1 & R^T+R^{T-1}+\cdots+R^2 & \cdots & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1} & R^T \\ R^T+R^{T-1}+\cdots+R^2 & R^T+R^{T-1}+\cdots+R^2 & R^T+R^{T-1}+\cdots+R^2 & & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1} & R^T \\ & \vdots & & \ddots & & \vdots & \\ R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1}+R^{T-2} & & R^T+R^{T-1}+R^{T-2} & R^T+R^{T-1} & R^T \\ R^T+R^{T-1} & R^T+R^{T-1} & R^T+R^{T-1} & \cdots & R^T+R^{T-1} & R^T+R^{T-1} & R^T \\ R^T & R^T & R^T & & R^T & R^T & R^T \end{vmatrix}$$

$$= \begin{vmatrix} R^0 & 0 & 0 & & 0 & 0 & 0 \\ R^1 & R^1 & 0 & \cdots & 0 & 0 & 0 \\ R^2 & R^2 & R^2 & & 0 & 0 & 0 \\ & \vdots & & \ddots & & \vdots & \\ R^{T-2} & R^{T-2} & R^{T-2} & & R^{T-2} & 0 & 0 \\ R^{T-1} & R^{T-1} & R^{T-1} & \cdots & R^{T-1} & R^{T-1} & 0 \\ R^T & R^T & R^T & & R^T & R^T & R^T \end{vmatrix} = \prod_{i=0}^{T} R^i > 0$$

As all of the leading principal minors are positive, $\mathbb{T} \succ 0$ (Positive definite).

$\therefore\ -\nabla^2 \Pi_Y = 2\beta \cdot \mathbb{T} \succ 0$ (Strictly convex).

Follower's problem has a unique optimal solution by Lemma 3.6.

■

As we have proved that the follower's problem has a unique optimal solution, let's show that there exists an explicit solution of the problem.

Proposition 3.1. The follower's optimization problem (3.23)-(3.24) in multi-period Stackelberg game has an explicit optimal solution.

Proof. By the first order condition, we can obtain

$$\frac{\partial \Pi_Y}{\partial y_t} = \sum_{l=t}^{T} R^l \cdot \left(-\beta \sum_{i=0}^{l} y_i + \left(\alpha + \gamma \cdot l - c_s - \beta\left(x_{1,l} + \sum_{i=0}^{l} x_{2,t} + \sum_{i=0}^{l} y_i\right)\right)\right) = 0$$

$$\sum_{l=t}^{T} \left(R^l \cdot \sum_{i=0}^{l} y_i^*\right) = \frac{1}{2\beta} \sum_{l=t}^{T} R^l \cdot (\alpha + \gamma \cdot l - c_S) - \frac{1}{2}\left(\sum_{l=t}^{T} R^l \cdot x_{1,l} + \sum_{l=t}^{T} \left(R^l \cdot \sum_{i=0}^{l} x_{2,i}\right)\right)$$

Let $H_t = R^t + R^{t+1} + \cdots + R^T$ and $S_t = t \cdot R^t + (t+1) \cdot R^{t+1} + \cdots + T \cdot R^T$.

$$\begin{bmatrix} H_t & H_t & \cdots & H_t & H_{t+1} & H_{t+2} & \cdots & H_T \end{bmatrix} \begin{bmatrix} y_0^* \\ y_1^* \\ \vdots \\ y_t^* \\ y_{t+1}^* \\ y_{t+2}^* \\ \vdots \\ y_T \end{bmatrix} = \frac{H_t \cdot \alpha - H_t \cdot c_s + \gamma \cdot S_t}{2\beta} - \frac{1}{2} \begin{bmatrix} 0 & 0 & \cdots & 0 & R^t & R^{t+1} & \cdots & R^T \end{bmatrix} \begin{bmatrix} x_{1,0} \\ x_{1,1} \\ \vdots \\ x_{1,t-1} \\ x_{1,t} \\ x_{1,t+1} \\ \vdots \\ x_{1,T} \end{bmatrix}$$

$$- \frac{1}{2} \begin{bmatrix} H_t & H_t & \cdots & H_t & H_{t+1} & H_{t+2} & \cdots & H_T \end{bmatrix} \begin{bmatrix} x_{1,0} \\ x_{1,1} \\ \vdots \\ x_{1,t} \\ x_{1,t+1} \\ x_{1,t+2} \\ \vdots \\ x_{1,T} \end{bmatrix}$$

Let $\mathbb{Y}$, $\mathbb{X}_1$, $\mathbb{X}_2$ as follows.

$$\mathbb{Y} = \begin{bmatrix} y_0^* & y_1^* & \cdots & y_T^* \end{bmatrix}^T, \ \mathbb{X}_1 = \begin{bmatrix} x_{1,0} & x_{1,1} & \cdots & x_{1,T} \end{bmatrix}^T, \ \mathbb{X}_2 = \begin{bmatrix} x_{2,0} & x_{2,1} & \cdots & x_{2,T} \end{bmatrix}^T$$

Then,

$$\mathbb{T} \cdot \mathbb{Y} = \frac{1}{2\beta} \begin{pmatrix} H_0 \cdot \alpha - H_0 \cdot c_s + \gamma \cdot S_0 \\ H1 \cdot \alpha - H_1 \cdot c_s + \gamma \cdot S_1 \\ \vdots \\ H_t \cdot \alpha - H_t \cdot c_s + \gamma \cdot S_t \\ \vdots \\ H_{T-1} \cdot \alpha - H_{T-1} \cdot c_s + \gamma \cdot S_{T-1} \\ H_T \cdot \alpha - H_T \cdot c_s + \gamma \cdot S_T \end{pmatrix} - \frac{1}{2} \begin{pmatrix} R^0 & R^1 & R^2 & & R^{T-2} & R^{T-1} & R^T \\ 0 & R^1 & R^2 & \dots & R^{T-2} & R^{T-1} & R^T \\ 0 & 0 & R^2 & & R^{T-2} & R^{T-1} & R^T \\ & \vdots & & \ddots & & \vdots & \\ 0 & 0 & 0 & & R^{T-2} & R^{T-1} & R^T \\ 0 & 0 & 0 & \cdots & 0 & R^{T-1} & R^T \\ 0 & 0 & 0 & & 0 & 0 & R^T \end{pmatrix} \mathbb{X}_1 - \frac{1}{2} \mathbb{T} \cdot \mathbb{X}_2$$

where $\mathbb{T}$ is from Theorem 3.1.

Subtracting $i+1$th row from ith row from above,

$$\begin{pmatrix} R^0 & 0 & 0 & & 0 & 0 & 0 \\ R^1 & R^1 & 0 & \dots & 0 & 0 & 0 \\ R^2 & R^2 & R^2 & & 0 & 0 & 0 \\ & \vdots & & \ddots & & \vdots & \\ R^{T-2} & R^{T-2} & R^{T-2} & & R^{T-2} & 0 & 0 \\ R^{T-1} & R^{T-1} & R^{T-1} & \dots & R^{T-1} & R^{T-1} & 0 \\ R^T & R^T & R^T & & R^T & R^T & R^T \end{pmatrix} \mathbb{Y} = \frac{1}{2\beta} \cdot \begin{pmatrix} R^0 \cdot (\alpha - c_s) \\ R^1 \cdot (\alpha - c_s) + \gamma R^1 \\ \vdots \\ R^t \cdot (\alpha - c_s) + \gamma \cdot t \cdot R^t \\ \vdots \\ R^{T-1} \cdot (\alpha - c_s) + \gamma \cdot (T-1) \cdot R^{T-1} \\ R^T \cdot (\alpha - c_s) + \gamma \cdot T \cdot R^T \end{pmatrix}$$

$$-\frac{1}{2} \cdot \begin{pmatrix} R^0 & 0 & 0 & & 0 & 0 & 0 \\ 0 & R^1 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & R^2 & & 0 & 0 & 0 \\ & \vdots & & \ddots & & \vdots & \\ 0 & 0 & 0 & & R^{T-2} & 0 & 0 \\ 0 & 0 & 0 & \cdots & 0 & R^{T-1} & 0 \\ 0 & 0 & 0 & & 0 & 0 & R^T \end{pmatrix} \mathbb{X}_1 - \frac{1}{2} \cdot \begin{pmatrix} R^0 & 0 & 0 & & 0 & 0 & 0 \\ R^1 & R^1 & 0 & \dots & 0 & 0 & 0 \\ R^2 & R^2 & R^2 & & 0 & 0 & 0 \\ & \vdots & & \ddots & & \vdots & \\ R^{T-2} & R^{T-2} & R^{T-2} & & R^{T-2} & 0 & 0 \\ R^{T-1} & R^{T-1} & R^{T-1} & \dots & R^{T-1} & R^{T-1} & 0 \\ R^T & R^T & R^T & & R^T & R^T & R^T \end{pmatrix} \mathbb{X}_2$$

Subtracting $R \times i$ th row from $i+1$th row from below,

$$\begin{pmatrix} R^0 & 0 & 0 & & 0 & 0 & 0 \\ 0 & R^1 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & R^2 & & 0 & 0 & 0 \\ & \vdots & & \ddots & & \vdots & \\ 0 & 0 & 0 & & R^{T-2} & 0 & 0 \\ 0 & 0 & 0 & \cdots & 0 & R^{T-1} & 0 \\ 0 & 0 & 0 & & 0 & 0 & R^T \end{pmatrix} \mathbb{Y} = \frac{1}{2\beta} \cdot \begin{pmatrix} R^0 \cdot (\alpha - c_s) \\ \gamma \cdot R^1 \\ \vdots \\ \gamma \cdot R^t \\ \vdots \\ \gamma \cdot R^{T-1} \\ \gamma \cdot R^T \end{pmatrix} - \frac{1}{2} \cdot \begin{pmatrix} R^0 & 0 & 0 & & 0 & 0 & 0 \\ -R^1 & R^1 & 0 & \dots & 0 & 0 & 0 \\ 0 & -R^2 & R^2 & & 0 & 0 & 0 \\ & \vdots & & \ddots & & \vdots & \\ 0 & 0 & 0 & & R^{T-2} & 0 & 0 \\ 0 & 0 & 0 & \cdots & -R^{T-1} & R^{T-1} & 0 \\ 0 & 0 & 0 & & 0 & -R^T & R^T \end{pmatrix} \mathbb{X}_1$$

$$-\frac{1}{2} \begin{pmatrix} R^0 & 0 & 0 & & 0 & 0 & 0 \\ 0 & R^1 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & R^2 & & 0 & 0 & 0 \\ & \vdots & & \ddots & & \vdots & \\ 0 & 0 & 0 & & R^{T-2} & 0 & 0 \\ 0 & 0 & 0 & \cdots & 0 & R^{T-1} & 0 \\ 0 & 0 & 0 & & 0 & 0 & R^T \end{pmatrix} \mathbb{X}_2$$

Then, we obtain

$$R^0 \cdot y_0^* = \frac{R^0 \cdot (\alpha - c_s)}{2\beta} - \frac{1}{2} R^0 \cdot x_{1,0} - \frac{1}{2} R^0 \cdot x_{2,0}$$

$$R^t \cdot y_t^* = \frac{\gamma \cdot R^t}{2\beta} - \frac{1}{2} R^t \cdot (x_{1,t} - x_{1,t-1}) - \frac{1}{2} R^t \cdot x_{2,t} \qquad \forall t = 1, 2, \dots, T$$

So, we can obtain explicit optimal solution of follower's objective function.

$$y_0^* = \frac{(\alpha - c_s)}{2\beta} - \frac{1}{2}x_{1,0} - \frac{1}{2}x_{2,0}$$

$$y_t^* = \frac{\gamma}{2\beta} - \frac{1}{2}(x_{1,t} - x_{1,t-1}) - \frac{1}{2}x_{2,t} \qquad \forall t = 1,2,\ldots,T$$

This $\mathbb{Y}$ is optimal solution for unconstrained problem of Π_Y. Let's show that this solution satisfies all the constraints (3.24) of follower's original problem.

$$\sum_{i=0}^{t} y_i^* = \frac{(\alpha - c_s) + \gamma \cdot t}{2\beta} - \frac{1}{2}x_{1,t} - \frac{1}{2}\sum_{i=0}^{t} x_{2,i} \qquad \forall t = 0,1,\ldots,T$$

Given $\mathbb{Y}$, the leader has to satisfy electricity price constraints (3.29).

$$(\alpha + \gamma \cdot t) - \beta(x_{1,T} + \sum_{i=0}^{T} x_{2,i} + \sum_{i=0}^{T} y_i) \geq c_S \qquad \forall t = 0,1,\ldots,T$$

Substituting $\sum_{i=0}^{t} y_i$ to $\sum_{i=0}^{t} y_i^*$,

$$\frac{(\alpha - c_s) + \gamma \cdot t}{2} - \frac{\beta}{2}(x_{1,t} + \sum_{i=0}^{t} x_{2,i}) \geq 0 \qquad \forall t = 0,1,\ldots,T$$

Dividing both side with $\beta > 0$,

$$\frac{(\alpha - c_s) + \gamma \cdot t}{2\beta} - \frac{1}{2}(x_{1,t} + \sum_{i=0}^{t} x_{2,i}) \geq 0 \qquad \forall t = 0,1,\ldots,T$$

$$\therefore \sum_{i=0}^{t} y_i^* \geq 0 \qquad \forall t = 0,1,\cdots,T$$

We have shown that the optimal solution derived under the assumption that the objective function is unconstrained satisfies all the original constraints. Therefore, $\mathbb{Y}$ is the explicit optimal solution for the follower's original problem.

$\blacksquare$

The leader solves modified profit maximization problem with given $\mathbb{Y}$ which is obtained from Proposition 3.1. Substituting for Y from the follower's problem, the leader gets updated objective function is as follows.

$$
\begin{aligned}
\Pi'_X = \sum_{t=0}^{T} R^t \cdot [(\frac{(\alpha + c_s) + \gamma \cdot t}{2} - \frac{\beta}{2}(x_{1,t} + \sum_{i=0}^{t} x_{2,i})) \cdot (x_{1,t} + \sum_{i=0}^{t} x_{2,i}) \\
-(ax_{1,t}^2 + bx_{1,t} + d) - c_F \cdot \sum_{i=0}^{t} x_{2,i} \\
-e_t \cdot ((x_{1,t} + \sum_{i=0}^{t} x_{2,i}) \cdot k_t - \delta_X \cdot \sum_{i=0}^{t} x_{2,i})]
\end{aligned}
\tag{3.32}
$$

Then, the leader's modified optimization problem is as follows.

$$
\max_{x_{1,t}, x_{2,t}} \quad \Pi'_X \tag{3.33}
$$

$$
\text{s.t.} \quad (x_{1,t} + \sum_{i=0}^{t} x_{2,i}) \cdot k_t - \delta_X \cdot \sum_{i=0}^{t} x_{2,i} \geq 0 \qquad \forall t = 0,1,\ldots,T \tag{3.34}
$$

$$
(k_t + \frac{\delta_Y}{2}) \cdot x_{1,t} + (k_t + \frac{\delta_Y}{2} - \delta_X) \cdot \sum_{i=0}^{t} x_{2,i} \leq \delta_Y \cdot \frac{(\alpha - c_s) + \gamma \cdot t}{2\beta} \qquad \forall t = 0,1,\ldots,T \tag{3.35}
$$

$$
\frac{(\alpha - c_s) + \gamma \cdot t}{2} - \frac{\beta}{2}(x_{1,t} + \sum_{i=0}^{t} x_{2,i}) \geq 0 \qquad \forall t = 0,1,\ldots,T \tag{3.36}
$$

$$
\sum_{i=0}^{t} x_{2,i} \geq 0 \qquad \forall t = 0,1,\cdots,T \tag{3.37}
$$

$$
x_{1,t} \geq 0 \qquad \forall t = 0,1,\ldots,T \tag{3.38}
$$

Theorem 3.2. The leader's modified optimization problem (3.33)-(3.38) in multi-period Stackelberg game has a unique optimal solution.

Proof.

Step1. Existence of optimal solution.

i. Each constraint is closed set. Intersection of these constraints ξ (feasible set) is nonempty closed set.

ii. Π'_X is continuous on ξ.

iii. $\lim_{\|X\|\to\infty} -\Pi'_X = \infty$ and $-\Pi'_X$ is a proper function.

∴ This problem attains an optimal solution X_1^*, X_2^* by Lemma 3.1.

Step2. Uniqueness of optimal solution

i. ξ is convex because constraints are affine set.

ii. We already showed that this problem has an optimal solution.

iii. Let's show that $-\Pi'_X$ is strictly convex.

Let Π_X^l as follows.

$$\Pi_X^l = R^l \cdot [(\frac{(\alpha + c_s) + \gamma \cdot l}{2} - \frac{\beta}{2}(x_{1,l} + \sum_{i=0}^{l} x_{2,i})) \cdot (x_{1,l} + \sum_{i=0}^{l} x_{2,i}) - (ax_{1,l}^2 + bx_{1,l} + d)$$
$$-c_F \cdot \sum_{i=0}^{l} x_{2,i} - e_l \cdot ((x_{1,l} + \sum_{i=0}^{l} x_{2,i}) \cdot k_l - \delta_X \cdot \sum_{i=0}^{l} x_{2,i})]$$

First, we calculate $\frac{\partial \Pi_X^l}{\partial x_{1,t}}$.

if $l \neq t$,

$$\frac{\partial \Pi_X^l}{\partial x_{1,t}} = 0$$

$$if\ \ l = t,$$

$$\frac{\partial \Pi_X^l}{\partial x_{1,t}} = R^t \cdot [-\frac{\beta}{2}(x_{1,t} + \sum_{i=0}^{t} x_{2,i}) + (\frac{\alpha + c_s + \gamma \cdot t}{2} - \frac{\beta}{2}(x_{1,t} + \sum_{i=0}^{t} x_{2,i})) - 2ax_{1,t} - e_t k_t]$$

$$= R^t \cdot [-(\beta + 2a)x_{1,t} - \beta \sum_{i=0}^{t} x_{2,i} + \frac{\alpha + c_s + \gamma \cdot t}{2} - e_t k_t]$$

So, we obtain

$$\frac{\partial \Pi_X'}{\partial x_{1,t}} = R^t \cdot [-(\beta + 2a)x_{1,t} - \beta \sum_{i=0}^{t} x_{2,i} + \frac{\alpha + c_s + \gamma \cdot t}{2} - e_t k_t]$$

Second, we calculate $\frac{\partial \Pi_X^l}{\partial x_{2,t}}$.

$$if\ \ l < t,$$

$$\frac{\partial \Pi_X^l}{\partial x_{2,t}} = 0$$

$$if\ \ l = t,$$

$$\frac{\partial \Pi_X^l}{\partial x_{2,t}} = R^t \cdot [-\frac{\beta}{2}(x_{1,t} + \sum_{i=0}^{t} x_{2,i}) + (\frac{\alpha + c_s + \gamma \cdot t}{2} - \frac{\beta}{2}(x_{1,t} + \sum_{i=0}^{t} x_{2,i})) - c_F - e_t(k_t - \delta_X)]$$

$$if\ \ l > t,$$

$$\frac{\partial \Pi_X^l}{\partial x_{2,t}} = R^l \cdot [-\frac{\beta}{2}(x_{1,l} + \sum_{i=0}^{l} x_{2,i}) + (\frac{\alpha + c_s + \gamma \cdot l}{2} - \frac{\beta}{2}(x_{1,l} + \sum_{i=0}^{l} x_{2,i})) - c_F - e_l(k_l - \delta_X)]$$

So, we obtain

$$\frac{\partial \Pi_X'}{\partial x_{2,t}} = R^l \cdot \sum_{l=t}^{T} [-\beta(x_{1,l} + \sum_{i=0}^{t} x_{2,l}) + \frac{\alpha + c_s + \gamma \cdot l}{2} - c_F - e_l(k_l - \delta_X)]$$

Third, we calculate second derivatives.

$$\frac{\partial^2 \Pi_X'}{\partial x_{1,t_1} \partial x_{1,t_2}} = \begin{cases} -R^{t_1} \cdot (\beta + 2a) & if\ t_1 = t_2 \\ 0 & if\ t_1 \neq t_2 \end{cases}$$

$$\frac{\partial^2 \Pi'_X}{\partial x_{1,t_1} \partial x_{2,t_2}} = \begin{cases} -R^{t_1} \cdot \beta & \textit{if } t_1 \geq t_2 \\ 0 & \textit{if } t_1 < t_2 \end{cases}$$

$$\frac{\partial^2 \Pi'_X}{\partial x_{2,t_1} \partial x_{2,t_2}} = -\beta(R^t + R^{t+1} + \cdots + R^T) \qquad \textit{where } t = \max(t_1, t_2)$$

Finally, we calculate $\nabla^2 \Pi'_X$.

$$\mathbb{A} = \nabla^2 \Pi'_X = \begin{array}{cc} & \begin{array}{cc} X_1 & X_2 \end{array} \\ \begin{array}{c} X_1 \\ \\ X_2 \end{array} & \begin{pmatrix} -R^0(\beta+2a) & 0 & 0 & & 0 & -R^0\beta & 0 & 0 & & 0 \\ 0 & -R^1(\beta+2a) & 0 & \cdots & 0 & -R^1\beta & -R^1\beta & 0 & \cdots & 0 \\ 0 & 0 & -R^2(\beta+2a) & & 0 & -R^2\beta & -R^2\beta & -R^2\beta & & 0 \\ & \vdots & & \ddots & \vdots & & \vdots & & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & -R^T(\beta+2a) & -R^T\beta & -R^T\beta & -R^T\beta & \cdots & -R^T\beta \\ -R^0\beta & -R^1\beta & -R^2\beta & & -R^T\beta & -H_0\beta & -H_1\beta & -H_2\beta & & -H_T\beta \\ 0 & -R^1\beta & -R^2\beta & \cdots & -R^T\beta & -H_1\beta & -H_1\beta & -H_2\beta & \cdots & -H_T\beta \\ 0 & 0 & -R^2\beta & & -R^T\beta & -H_2\beta & -H_2\beta & -H_2\beta & & -H_T\beta \\ & \vdots & & \ddots & \vdots & & \vdots & & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & -R^T\beta & -H_T\beta & -H_T\beta & -H_T\beta & \cdots & -H_T\beta \end{pmatrix} \end{array}$$

$$\mathbb{A} \prec 0 \Leftrightarrow \mathbb{B} \succ 0 \quad \textit{where}\, \mathbb{B} = -\mathbb{A}$$

Let $\mathbb{k}$ and $\mathbb{U}$ as follows.

$$\mathbb{k} = \begin{pmatrix} R^0 & 0 & 0 & & 0 \\ 0 & R^1 & 0 & \cdots & 0 \\ 0 & 0 & R^2 & & 0 \\ & \vdots & & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & R^T \end{pmatrix}, \qquad \mathbb{U} = \begin{pmatrix} R^0 & R^1 & R^2 & & R^T \\ 0 & R^1 & R^2 & \cdots & R^T \\ 0 & 0 & R^2 & & R^T \\ & \vdots & & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & R^T \end{pmatrix}$$

We already have shown that $\mathbb{T} \succ 0$ in Theorem 3.1.

$$\mathbb{T} = \begin{pmatrix} R^T + R^{T-1} + \cdots + R^0 & R^T + R^{T-1} + \cdots + R^1 & R^T + R^{T-1} + \cdots + R^2 & & R^T + R^{T-1} + R^{T-2} & R^T + R^{T-1} & R^T \\ R^T + R^{T-1} + \cdots + R^1 & R^T + R^{T-1} + \cdots + R^1 & R^T + R^{T-1} + \cdots + R^2 & \cdots & R^T + R^{T-1} + R^{T-2} & R^T + R^{T-1} & R^T \\ R^T + R^{T-1} + \cdots + R^2 & R^T + R^{T-1} + \cdots + R^2 & R^T + R^{T-1} + \cdots + R^2 & & R^T + R^{T-1} + R^{T-2} & R^T + R^{T-1} & R^T \\ & \vdots & & \ddots & & \vdots & \\ R^T + R^{T-1} + R^{T-2} & R^T + R^{T-1} + R^{T-2} & R^T + R^{T-1} + R^{T-2} & & R^T + R^{T-1} + R^{T-2} & R^T + R^{T-1} & R^T \\ R^T + R^{T-1} & R^T + R^{T-1} & R^T + R^{T-1} & \cdots & R^T + R^{T-1} & R^T + R^{T-1} & R^T \\ R^T & R^T & R^T & & R^T & R^T & R^T \end{pmatrix} \succ 0$$

Then,

$$\mathbb{k}^{-1} = \begin{pmatrix} \frac{1}{R^0} & 0 & 0 & & 0 \\ 0 & \frac{1}{R^1} & 0 & \cdots & 0 \\ 0 & 0 & \frac{1}{R^2} & & 0 \\ & \vdots & & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \frac{1}{R^T} \end{pmatrix}$$

$$\mathbb{U}\mathbb{K}^{-1}\mathbb{U}^T = \begin{pmatrix} R^0 & R^1 & R^2 & & R^T \\ 0 & R^1 & R^2 & \cdots & R^T \\ 0 & 0 & R^2 & & R^T \\ & \vdots & & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & R^T \end{pmatrix} \cdot \begin{pmatrix} \frac{1}{R^0} & 0 & 0 & & 0 \\ 0 & \frac{1}{R^1} & 0 & \cdots & 0 \\ 0 & 0 & \frac{1}{R^2} & & 0 \\ & \vdots & & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \frac{1}{R^T} \end{pmatrix} \cdot \begin{pmatrix} R^0 & 0 & 0 & & 0 \\ R^1 & R^1 & 0 & \cdots & 0 \\ R^2 & R^2 & R^2 & & 0 \\ & \vdots & & \ddots & \vdots \\ R^T & R^T & R^T & \cdots & R^T \end{pmatrix} = \mathbb{T}$$

so,

$$\mathbb{B} = \begin{pmatrix} (\beta+2a)\mathbb{k} & \beta\mathbb{U}^T \\ \beta\mathbb{U} & \beta\mathbb{T} \end{pmatrix}$$

By Lemma 3.7,

$$\mathbb{B} \succ 0 \Leftrightarrow \beta\mathbb{T} - \beta^2\mathbb{U}\frac{1}{\beta+2a}\mathbb{k}^{-1}\mathbb{U}^T \succ 0$$

$$\beta\mathbb{T} - \beta^2\mathbb{U}\frac{1}{\beta+2a}\mathbb{K}^{-1}\mathbb{U}^T = \beta\mathbb{T} - \frac{\beta^2}{\beta+2a}\mathbb{U}\mathbb{K}^{-1}\mathbb{U}^T = \beta\mathbb{T} - \frac{\beta^2}{\beta+2a}\mathbb{T} = \frac{2a\beta}{\beta+2a}\mathbb{T} \succ 0$$

$(\because a, \beta > 0)$

$\therefore -\Pi'_X$ is strictly convex.

With i), ii) and iii), leader's problem has a unique optimal solution by Lemma 3.6.

■

Corollary 3.1. The multi-period Stackelberg game (3.23)-(3.24) and (3.26)-(3.31) has a unique Nash Equilibrium.

Proof. The follower's optimization problem has a unique optimal solution by Theorem 3.1. Given the explicit optimal solution of the follower from Proposition 3.1, the leader's problem has a unique optimal solution by Theorem 3.2. As both the leader and the follower has unique optimal solution, neither firms have incentive to deviate from the equilibrium. So, there exists a unique Nash equilibrium for the multi-period Stackelberg game.

■

Chapter 4

Numerical Examples and Analysis

4.1 Initial Parameters

In this chapter, we use numerical examples to analyze the game models presented in this study. The initial value settings for the analysis is shown in Table 4. 1. It is assumed that the government proposes a quota obligation plan for 10 years, and that the obligation is increased by 1% each year. It is assumed that the large-scale power generation company adopt renewable energy technology that is cheaper than the renewable energy generation company, and sensitivity analysis is conducted on the cost of each technology.

Table 4. 1 : Initial parameters

Parameter	Value	Parameter	Value
T	10	c_F	125 (million won/GWh)
r	0.03	c_S	150 (million won/GWh)
α	300	a	0.00015
β	0.0004	b	26
γ	10	δ_X, δ_Y	1
e_t	$10-t$	k_t	$0.01 \cdot t$

4.2 Comparison of Single-period and Multi-period Stackelberg Game Model

Based on the initial value presented above, the result of solving the optimization problem for the single-period and multi-period Stackelberg game is shown in Figure 4.1. In single period model, each company makes a new decision at every time period based on information about the previous periods. In the multi-period model, on the other hand, both companies conduct decision making for all future periods at once in the period 0. Figure 4.1 shows that the optimal decisions of both companies are different in the single-period and multi-period model. In the single-period model, the leader was more conservative in renewable energy investment than in the multi-period model, and in the last period it was found that it disposes of all renewable energy facilities. Furthermore, it was found to reduce the amount of its own obligations by controlling the electricity generation of each power source in order to maximize its profit in a single-period model. This difference occurs because in the single-period model, when the companies make decisions to expand renewable energy capacity, they adopt decisions that have already made previously and do not consider the remaining periods.
Table 4.2 shows the discounted profits of the firms in the single-period and multi-period model and the difference of them. We found that both the leader and follower earns a greater total discounted profit in the multi-period model than the single-period model. Furthermore, in the multi-period model, the discounted profits of the leader gradually increase every period, but not in the single-period model.

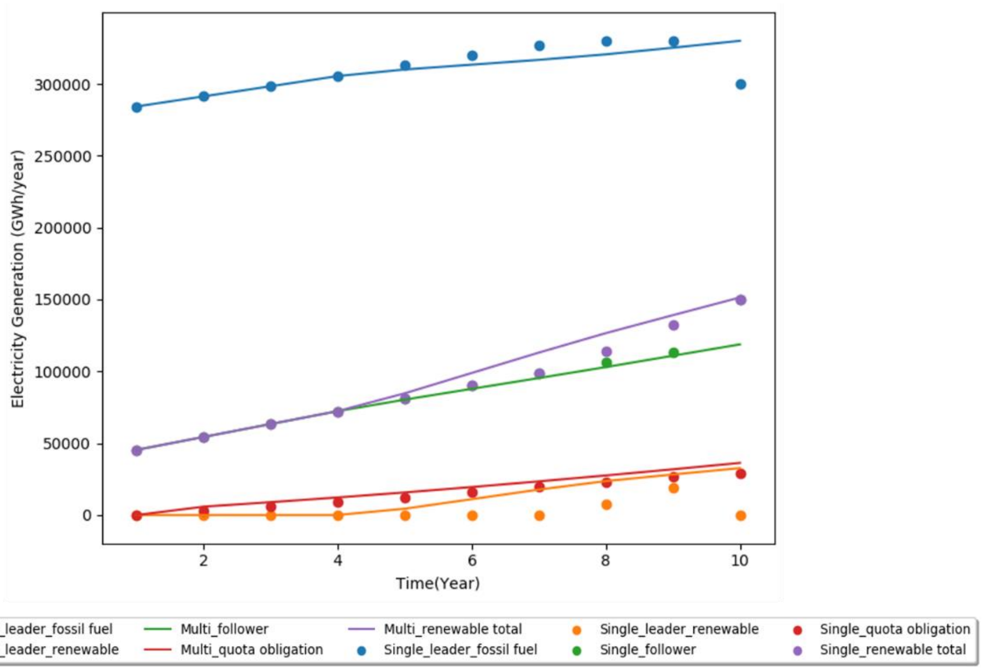

Figure 4.1: Annual electricity generation of the leader and the follower

Table 4. 2 : The discounted profits of the leader and the follower in the single-period and multi-period model

Period		0	1	2	3	4	5	6	7	8	9	10	Total
Leader	Multi	28,286	28,834	29,365	29,877	30,372	30,856	31,327	31,786	32,231	32,662	33,079	338,675
	Single	28,286	28,860	29,410	29,936	30,438	30,916	31,370	31,805	32,235	31,960	30,043	335,258
	Diff.	0	-25	-45	-59	-65	-60	-43	-19	-5	702	3,036	3,417
Follower	Multi	1,957	2,492	3,049	3,625	4,119	4,577	5,046	5,540	6,065	6,596	7,123	50,190
	Single	823	1,179	1,598	2,082	2,629	3,240	3,914	4,517	5,103	9,000	14,063	48,147
	Diff.	1,134	1,313	1,451	1,544	1,490	1,337	1,132	1,023	962	-2,404	-6,939	2,042

(Billion won)

Figure 4.2 shows the trend in the ratio of renewable energy output to overall power production over time. The market constructed with initial parameters produced more renewable power than quota obligation. Figure 4.1 shows that the total amount of renewable energy produced in the last period is larger in the multi-period model, but in Figure 4.2, the final diffusion rate of renewable energy is higher in the single-period model.

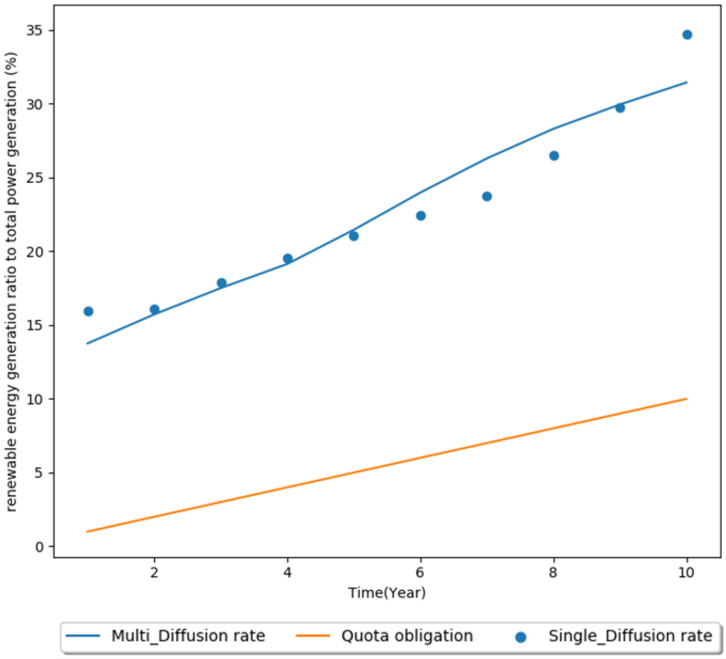

Figure 4.2: Renewable energy proportion to the total electricity generation

4.3 Sensitivity Analysis

In this chapter, we analyzes how key variables in the multi-period Stackelberg game model affect the proliferation of renewable energy and the profits of each company. Figure 4.3 shows the results of the sensitivity analysis for the final electrical output under each quota obligation scenario. In the figure, the higher the quota obligation target, the more the leader reduces fossil fuel power generation and increases renewable energy generation facilities. On the other hand, as the quota obligation increases, the leader increases the renewable energy facilities, which causes the REC sales revenue to decrease, which reduces the renewable energy generation of the follower. The analysis results show that the amount of renewable energy generation of the leader does not exceed that of the follower until certain amount of obligation.

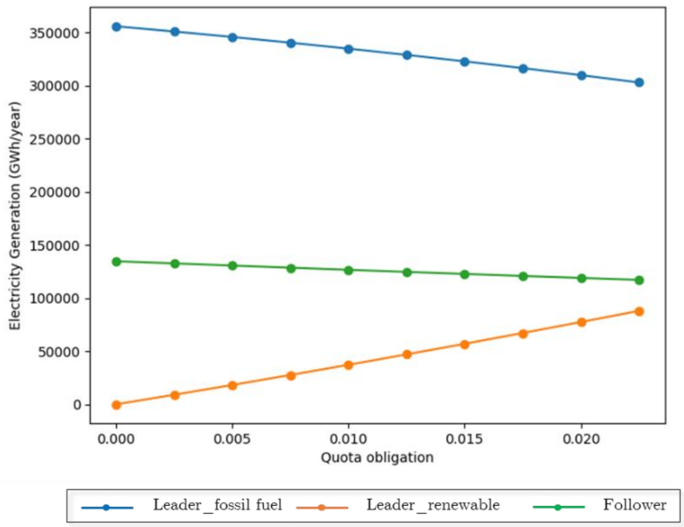

Figure 4.3: Electricity generation in the last period with various quota obligations

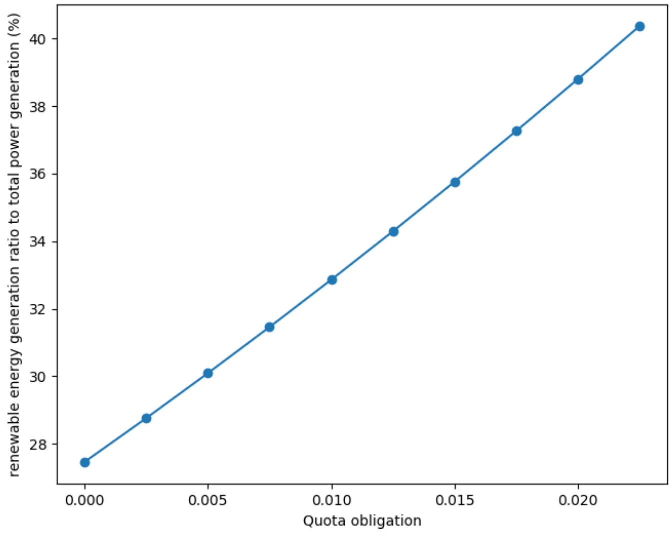

Figure 4.4: Proportion of renewable energy to the total electricity generation with various quota obligations

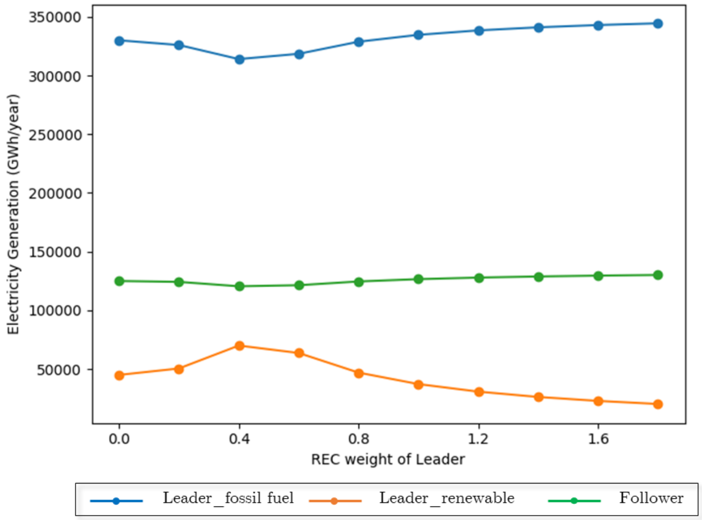

Figure 4.5: Annual electricity generation with various REC weights

Figure 4.4 shows the spread rate of renewable energy for each scenario in the same situation as figure 4.3, and we can figure out that the proportion of renewable energy generation increases almost linearly as the quota obligation increases.

Figure 4.5 shows the results of the sensitivity analysis for the final electrical output under each REC weight scenario. When the leader's REC weight is low, he produces a small amount of renewable energy and then produces the maximum at a certain point as 0.4, after which he continues to reduce the investment in renewable energy even if a higher weight is assigned. The reason why the graph takes this form is that the obligation to be satisfied by the leader can be efficiently fulfilled in a smaller amount after a certain REC weight. Therefore, as the REC weight increases, the leader increases the amount of fossil fuel power generation. On the other hand, such critical point appears later in single-period model.

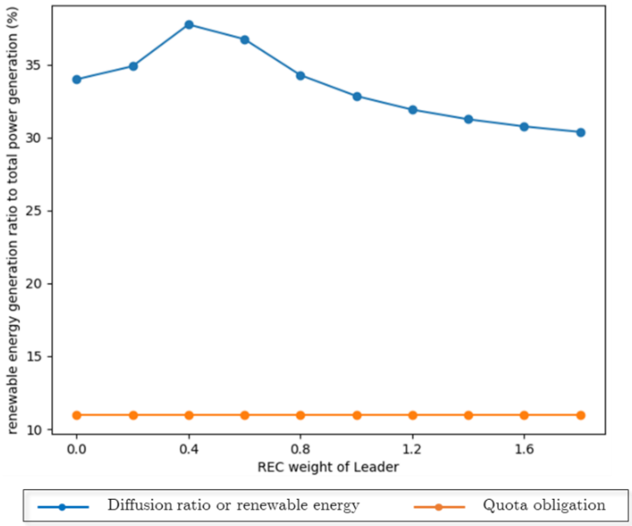

Figure 4.6: Proportion of renewable energy to the total electricity generation with REC weights

Figure 4.6 shows the spread rate of renewable energy for each scenario in the same situation as figure 4.5, and we can figure out that the proportion of renewable energy generation increases until 0.4 and then decreases. Therefore, we can see that the excessive REC weight given to the leader can negatively affect the spread of renewable energy.

Figure 4.7 shows the results of the sensitivity analysis for the final electrical output under each renewable energy production cost scenario. In the figure, it can be observed that in scenario 5, where the leader's renewable energy generation cost is equal to that of the follower, the leader's renewable energy generation increases. In other words, if the leader's renewable energy generation costs are greater than the sum of the power generation costs and REC prices, it is confirmed that no investment is made in renewable energy, but if the cost is small, only a certain amount of capacity is secured. Figure 4.8 shows the spread rate of renewable energy for each scenario in the same situation as figure 4.7, and we can figure out that the proportion of renewable energy generation increases dramatically at scenario 5 and then decreases.

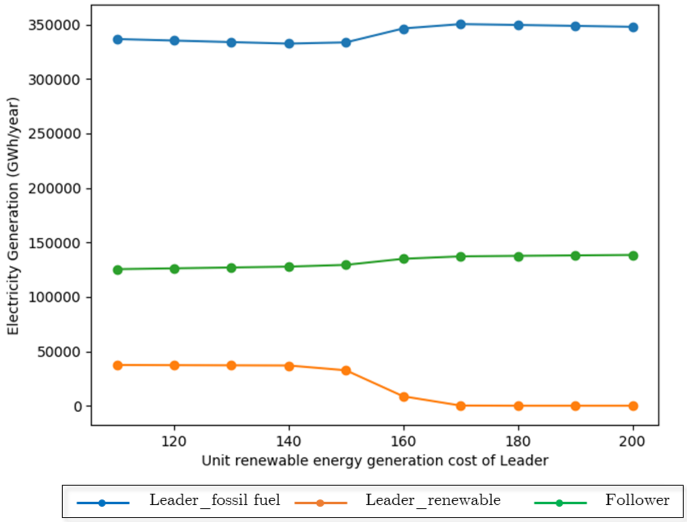

Figure 4.7: Annual electricity generation with various generation costs

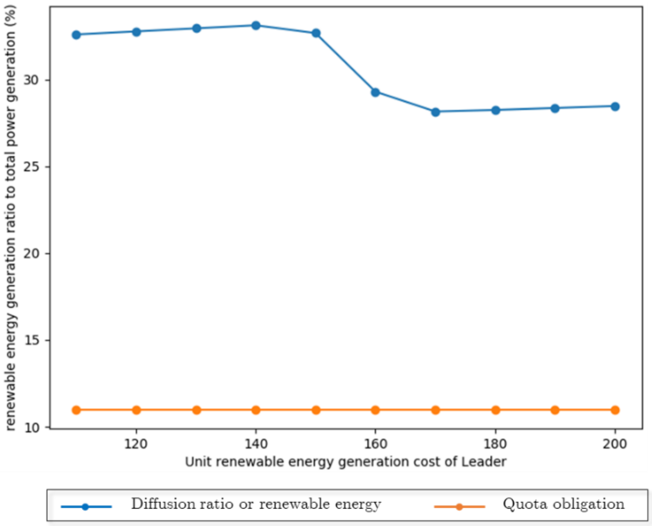

Figure 4.8: Proportion of renewable energy to the total electricity generation with various generation costs

Figure 4.9 shows the diffusion rate of renewable energy by the cost of renewable power generation of the leader and follower. The figure shows that the share of renewable energy is increasing in proportion to the amount of reduction in the power generation costs. On the other hand, the renewable energy generation cost of the leader has a relatively small impact on the spread of renewable energy, but it can be confirmed that the renewable energy diffusion can be greatly increased if it is less than a specific amount.

Figure 4.10 represents the discounted profit of the leader by the cost of renewable power generation of the leader and follower. In the figure, it can be seen that the leader's revenue is significantly affected by the cost of the follower's power generation rather than its own. The reason is that the higher the cost of power generation of the follower, the weaker the competitiveness in the power market, so the leader can enjoy more profits. Similarly, Figure 4.11 shows that the discounted profit of the follower is greatly affected by its unit generation cost.

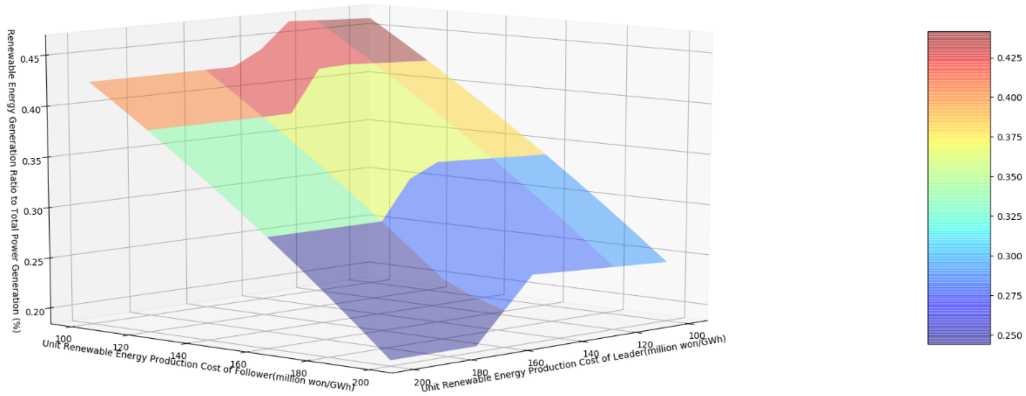

Figure 4.9: The diffusion rate of renewable energy by the cost of renewable power generation of the leader and follower

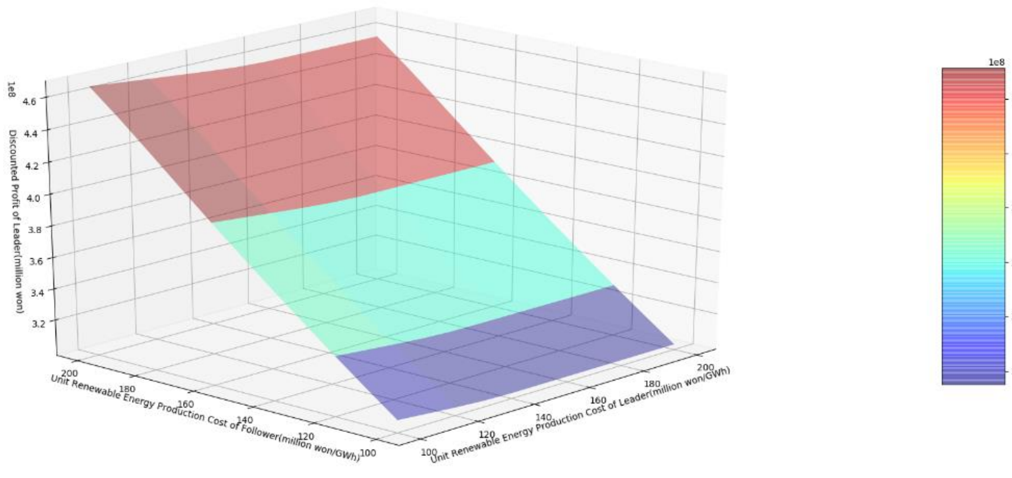

Figure 4.10: The discounted profit of the leader by the cost of renewable power generation of the leader and follower

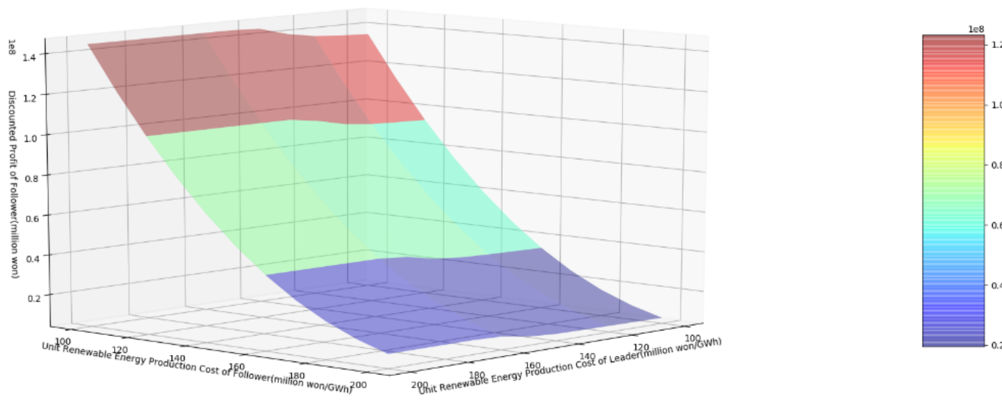

Figure 4.11: The discounted profit of the follower by the cost of renewable power generation of the leader and follower

Figure 4.12 shows the diffusion rate of renewable energy by the annual increasing amount of quota obligation and the annual demand increase in electricity market γ. In the figure, the increase in market demand has a greater impact on the spread of renewable energy than quota obligation, and the greater the annual increase in quota obligation, the greater its power. Quota obligation also has a greater impact on the proliferation of renewable energy if the market demand growth is greater. Thus, from the perspective of renewable energy diffusion, the rate of increase in demand in the power market and the rate of increase in quota obligation are synergistic with each other.

In Figures 4.13 and 4.14, we can see that fluctuations in electricity market demand have a greater impact on the profits of both companies than the increase or decrease in quota obligations.

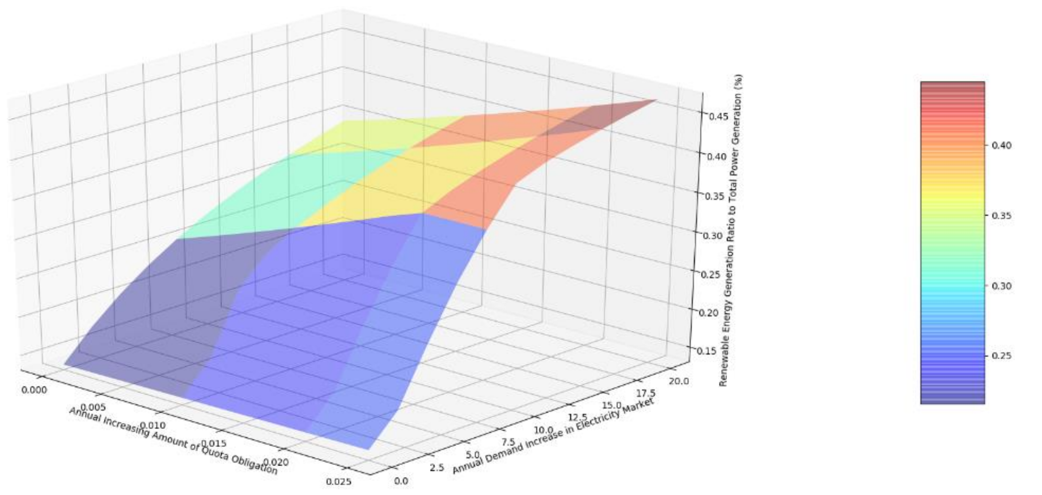

Figure 4.12: The diffusion rate of renewable energy by the annual increasing amount of quota obligation and the annual demand increase in electricity market

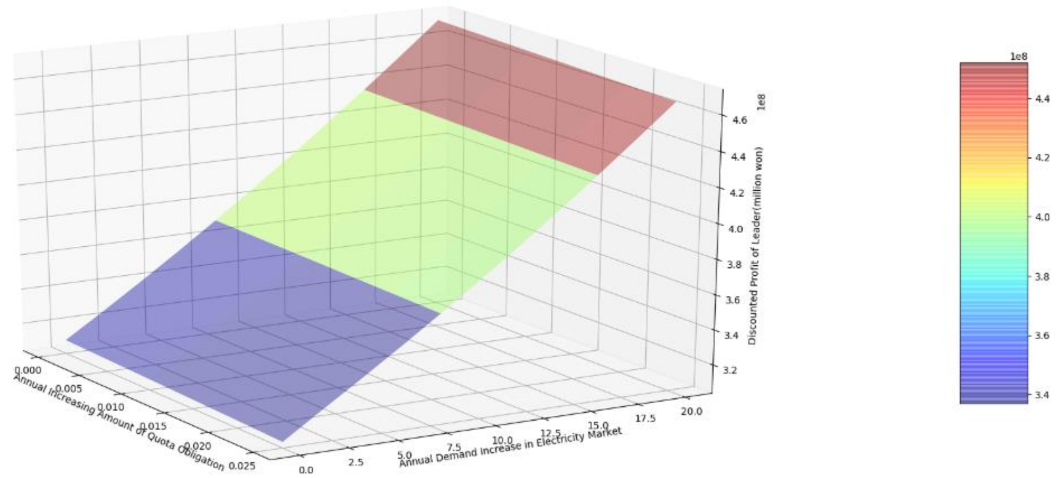

Figure 4.13: The discounted profit of the leader by the annual increasing amount of quota obligation and the annual demand increase in electricity market

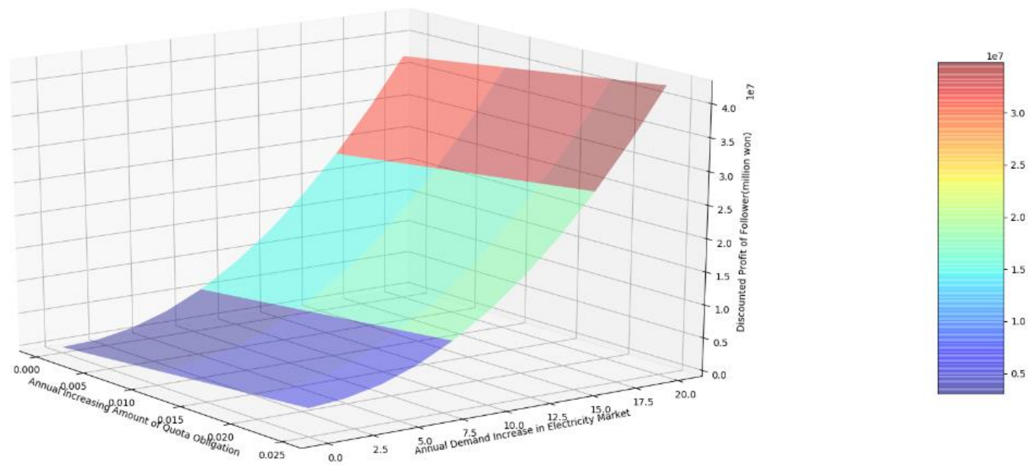

Figure 4.14: The discounted profit of the follower by the annual increasing amount of quota obligation and the annual demand increase in electricity market

Chapter 5

Conclusion

We proposed a two stage single-period and multi-period Stackelberg game for renewable power capacity expansion in renewable portfolio standard. Both game model are proved to have a unique Nash equilibrium. Numerical experiments were conducted and we found that the optimal generation strategy of the leader and follower is different between the multi-period and single-period Stackelberg game model. We also found several important insights of the RPS system.

First, the higher the quota allocation target, the more the leader reduces fossil fuel power generation and increases renewable energy generation facilities. However, as it reduces the contraction of REC between the leader and the follower, the follower reduces its renewable energy generation. But still, the total renewable power increases.

Second, we found that there exists a critical point of the leader's REC weight which maximizes the diffusion of renewable energy. This happens because if the REC weight is higher than the point, the leader can be efficiently fulfilled with smaller amount of renewable power generation.

Third, the follower's production cost greatly affect the proliferation of renewable energy. Furthermore, there exist a point where a small decrease of the leader's renewable production cost makes the diffusion rate of renewable energy jump.

Finally, the rate of increase in demand in the power market and the rate of increase in quota obligation are synergistic with each other from the perspective of renewable energy diffusion.

This study could contribute to the government that wants to introduce renewable portfolio standard in the future or to the government that has already adopted it and wants to improve it.

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국문초록

재생에너지 공급의무화제도(RPS) 하에서 정부는 전력시장에 화석연료를 사용하는 대규모 발전사업자에게 부과하는 신재생에너지 발전 의무량에 대한 장기적인 계획을 제시한다. 본 논문은 기존 발전시장 참여자인 화석연료 발전사업자와 신규 참여자인 신재생에너지 발전사업자의 경쟁관계를 다기간 스탁켈베르그 게임(multi-period Stackelberg game)을 통해 모형화하고, 신재생에너지 발전 의무량 등이 신재생에너지 확산에 미치는 영향에 대해 확인한다. 본 연구에서 제시한 모형에 유일한 내쉬 균형이 존재한다는 것을 증명하였으며, 이를 바탕으로 수치예제를 활용하여 재생에너지 공급의무화제도를 분석하였다. 또한 단기간 스탁켈베르그 게임의 해와 다기간 모형의 해가 다르다는 것을 확인하였고, 그 이유는 매 시점에 최적의 재생에너지발전 확장용량을 결정하는 것이 다기간의 최적 전략을 한번에 세우는 것 보다 비효율적이기 때문이라는 것을 확인하였다. 그리고 재생에너지 확산을 최대화하는 최적의 REC 가중치가 존재한다는 것을 확인하였다. 마지막으로, 본 연구에서는 전력 시장의 수요 증가와 재생에너지 공급의무량의 증가가 시너지효과를 내어 재생에너지 확산에 기여할 수 있다는 것을 확인하였다.

주요어: 신재생에너지, 재생에너지 공급의무화제도, 다기간 스탁켈베르그 게임, 재생에너지 지원제도, 전력시장

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